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EMISSIONS OF HYDROCARBONS TO THE ATMOS-
PHERE FROM SEALS ON PUMPS AND COMPRESSORS

Bernard J. Steigerwald

Joint District, Federal and State Project for the
Evaluation of Refinery Emissions

April 1958

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**JOINT DISTRICT, FEDERAL AND STATE PROJECT
FOR THE EVALUATION OF REFINERY EMISSIONS**



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REPORT NUMBER 8

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ATMOSPHERE FROM SEALS ON PUMPS
AND COMPRESSORS**

April, 1968

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JOINT DISTRICT, FEDERAL AND STATE PROJECT
FOR THE EVALUATION OF REFINERY EMISSIONS

REPORT NUMBER 6

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Details of illustrations in
this document may be better
studied on microfiche.

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FOREWORD

In August 1955, the Los Angeles County Air Pollution Control District, the California State Department of Public Health, and the U. S. Public Health Service inaugurated the Joint District, Federal, and State Project for the Evaluation of Refinery Emissions in Los Angeles County. The Western Oil and Gas Association, representing the petroleum industry, also participated in the project. This report presents the results of one of the studies of the Joint Project.

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JOINT DISTRICT, FEDERAL AND STATE PROJECT FOR THE EVALUATION OF REFINERY EMISSIONS

EMISSIONS OF HYDROCARBONS TO THE ATMOSPHERE FROM SEALS ON PUMPS AND COMPRESSORS

IN BRIEF

One phase of the Joint District, Federal and State Project for the Evaluation of Refinery Emissions was the study of hydrocarbon leakage from seals on pumps and compressors. This report details the techniques and conclusions of the study.

Questionnaires were sent to all major refineries requesting the type, product, operation, seal type and number of seals for each pump and compressor in the refinery. Similar information was obtained from the smaller refineries during field inspection trips. The companies reported a total of 1985 pumps having 2786 seals and 162 compressors equipped with 345 seals. Pumps handling hydrocarbons having a Reid vapor pressure less than 0.5 pound and units equipped with seals venting to vapor recovery systems were not included in this study.

Using the census data, pumps were classified into 27 unique combinations of pump type, seal type, product and pump operation. Approximately 15 per cent of the seals in each group were checked. A total of 473 pump seals were inspected and these had an average loss of 4.2 pounds of hydrocarbons per day. This average loss is based on emissions from 75 measured leaks and loss estimates for 95 small leaks. All compressor seals were tested. These lost an average of 8.5 pounds per day per seal.

The test procedure for both pumps and compressors involved an initial search for hydrocarbons in the vicinity of the seal using a combustible gas indicator. Where necessary, this search was followed by loose shrouding of the seal area, drawing air at a measured rate into the shroud and across the seal by continual evacuation of the atmosphere in the shroud, and the determination of the hydrocarbon concentration in the air stream.

The hydrocarbon leakage from pump seals, calculated by projecting the field test data to the reported number of seals in each group was found to be 6 tons of hydrocarbons per day. Emissions from seals on compressors were 1.5 tons per day.

Additional analyses of the field data showed that pumps handling the highly volatile materials (products having a Reid vapor pressure greater than 26 pounds) contribute most of the total hydrocarbon leakage through pump seals. The pumps in this group comprise 28 per cent of the total number and are responsible for 70 per cent of the total emissions.

JOINT DISTRICT, FEDERAL AND STATE PROJECT FOR THE EVALUATION OF REFINERY EMISSIONS

EMISSIONS OF HYDROCARBONS TO THE ATMOSPHERE FROM SEALS ON PUMPS AND COMPRESSORS

INTRODUCTION

One phase of the Joint District, Federal and State Project for the Evaluation of Refinery Emissions called for the study of hydrocarbon emissions from pumps and compressors in oil refineries in Los Angeles County. Under normal operation the only source of emissions from centrifugal pumps and compressors is the intersection of the drive shaft and the impeller casing. On reciprocating units leakage is possible at the entrance of the connecting rod into the cylinder or fluid chamber.

There are a number of methods and devices used to retard leakage of the product through these junctions. These include packings, mechanical seals, throttle bushings, floating rings, canned pumps, electromagnetic pumps and frozen seals.⁽¹⁾ The selection of the proper method depends on temperature, product, pressure and type of pump being used. For the transfer of hydrocarbons in the oil industry packing or mechanical seals are usually sufficient and are almost universally used.

In general, packed seals consist of stuffing boxes filled with woven, braided, twisted or laminated rubber, leather, fiber, metal or special compounds.⁽²⁾ These boxes, which surround the moving shaft, are provided with "take-up" rings which allow compression of the packing. This compression forces the packing material against the moving shaft and effects the seal (Figure 1). Packing can be used to seal both rotary and reciprocating shaft motions.

A simple mechanical seal has two rings with wearing faces at right angles to the shaft. One ring (the sealing ring) is fastened to the shaft and rotates with it while the other is stationary and held against

(1) Tracy, H. E., "Select Best Pump Seal," Chemical Engineering, p. 239-54, (April 1957)

(2) Elonka, S., "Mechanical Packing," Power, Vol. 99, No. 3, p. 107-130, (March 1955)

the pump casing. The wearing faces are generally lubricated with a film of the product being pumped and effect the closure⁽³⁾ (Figure 2). Mechanical seals can be used only on units having a rotary shaft motion.

The design of packed and mechanical seals usually found in oil refineries are much more complex than those shown in Figures 1 and 2 due to provisions for cooling, lubricating and balancing the seals.

In normal service both packed and mechanical seals can leak hydrocarbons. These losses may be vapor or liquid and occur when shafts become scarred or move eccentrically, or through failure of the packing or seal faces. The rate at which this destruction of seal efficiency progresses depends upon the abrasive and corrosive properties of the product handled and the type of maintenance.

In an effort to define the magnitude of hydrocarbon losses from pumps and compressors a complete field testing program was initiated by the Joint Project. This report details the techniques and results of the study.

(3) Elonka, S., "Mechanical Seals," Power, Vol. 100, No. 3, p. 109-133, (March 1956)

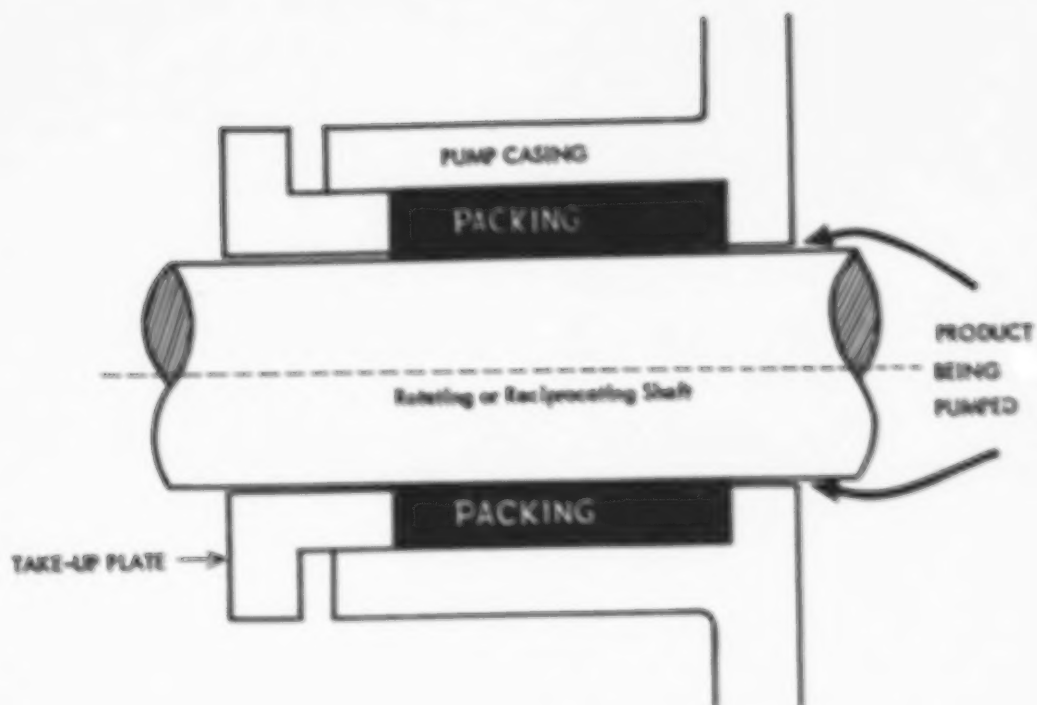


Figure 1. Diagram of a simple packed seal.

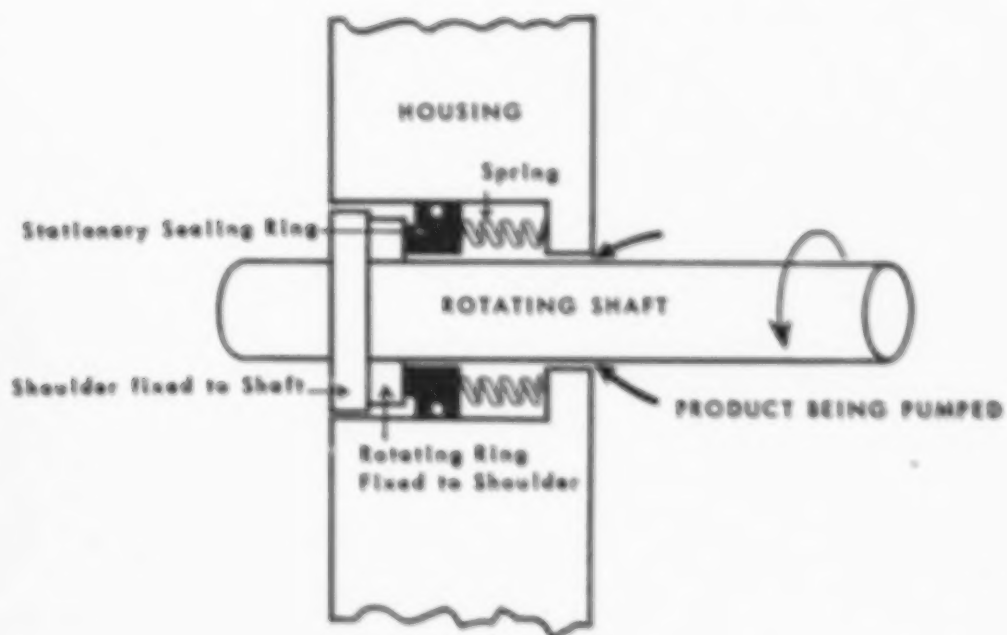


Figure 2. Diagram of a simple mechanical seal.

CENSUS OF PUMPS AND COMPRESSORS

In order to design a realistic sampling program and allow valid data extrapolation it was necessary to acquire information concerning the number, distribution, type, and usage of pumps and compressors in oil refineries in Los Angeles County.

Pump Census

In anticipation of this study, the Joint Project polled the major refineries for pump information in July 1956. When the present study was inaugurated it was appreciated that some changes would have been made in the past year, particularly in the total number of installations and the ratio of mechanical to packed seals. However, since the changes that would occur in a year would not greatly affect the results it was decided to use the 1956 data for the present study. The following information was available from all major refineries for each pump handling hydrocarbons with a Reid vapor pressure greater than 0.5 pound.

1. Pump designation - refinery identification number.
2. Type of pump - centrifugal, reciprocating, gear, etc.
3. Pump operation - continuous, intermittent or spare.
4. Temperature of product being pumped.
5. Number and type of seal - mechanical, packed, etc.
6. Product being pumped:
 - L. P. G. - defined for this study as hydrocarbons having a Reid vapor pressure greater than 26 pounds.
 - Gasoline - defined for this study as hydrocarbons having a Reid vapor pressure of 5-26 pounds.

Naphtha - defined for this study as hydrocarbons having a Reid vapor pressure of 0.5-5 pounds.

Crude Oil

Pump census data from the smaller refineries not covered in the original survey were solicited during field testing trips to these plants.

Table I summarizes the pump census data in the form finally used in the design of the sampling program. Units with seals venting to vapor recovery systems and installations with no seals such as canned or electromagnetic pumps, or pumps handling a product with Reid vapor pressures less than 0.5 pound, are not included in Table I.

Compressor Census

In June 1957, a questionnaire was sent to the Western Oil and Gas Association requesting compressor information from all member refineries in Los Angeles County. The following data were reported for all compressors handling gases containing more than 15 per cent hydrocarbons:

1. Compressor designation - refinery identification number.
2. Type of Compressor - reciprocating or centrifugal.
3. Compressor operation - continuous, intermittent or spare.
4. Operating pressure.
5. Number and type of seal - mechanical, packed, etc.
6. Refinery unit served by compressor - T.C.C. unit, vapor recovery, etc.

Non-WOGA member refineries were polled during the field testing visits and similar information recorded.

An examination of the compressor census data revealed that very few centrifugal or mechanical seal units are operating in these refineries. The great majority of installations are reciprocating compressors in continuous operation and equipped with some form of packed seal or throttle bushing. This, and the decision to test all compressors, obviated

Table I

TABULATION OF REFINERY PUMP CENSUS DATA

Group Number	Type of Seal	Type of Pump	Pump Operation	Product Pumped Pounds(*) Reid	Number of Pumps	Number of Seals
1	Mechanical	Centrifugal(**)	Spare	> 26	63	76
2	"	"	"	5-26	66	82
3	"	"	"	0.5-5	48	66
4	"	"	Intermittent	> 26	100	127
5	"	"	"	5-26	174	266
6	"	"	"	0.5-5	52	56
7	"	"	Continuous	>26	132	163
8	"	"	"	5-26	153	191
9	"	"	"	0.5-5	117	150
TOTAL					905	1177
10	Packed	Centrifugal(**)	Spare	>26	54	92
11	"	"	"	5-26	54	78
12	"	"	"	0.5-5	47	68
13	"	"	Intermittent	>26	31	49
14	"	"	"	5-26	124	179
15	"	"	"	0.5-5	68	103
16	"	"	Continuous	>26	69	100
17	"	"	"	5-26	109	175
18	"	"	"	0.5-5	84	124
TOTAL					640	968
19	Packed	Reciprocating	Spare	>26	22	26
20	"	"	"	5-26	21	32
21	"	"	"	0.5-5	23	38
22	"	"	Intermittent	>26	55	72
23	"	"	"	5-26	124	173
24	"	"	"	0.5-5	83	150
25	"	"	Continuous	>26	40	60
26	"	"	"	5-26	34	40
27	"	"	"	0.5-5	38	50
TOTAL					440	641
TOTALS FOR ALL PUMPS AND SEALS					1985	2786

(*) Pumps handling crude oil were included in the 0.5-5 Reid vapor pressure classification.

(**) Centrifugal pumps include a few gear pumps and any other unit having a rotary shaft motion.

a detailed breakdown and study of the census data. Table II shows the total number of compressors with seals venting to the atmosphere and to vapor recovery systems. Installations handling gases containing less than 15 per cent hydrocarbons are not included in this tabulation.

Table II

RESULTS OF REFINERY COMPRESSOR CENSUS

Classification	Number of Compressors	Number of Seals
Units venting to atmosphere	162	345
Units venting to vapor recovery systems	20	45
Totals	182	390

TESTING PROCEDURE

The testing procedure used in this study was essentially the same for both pumps and compressors. It involved an initial semi-quantitative search for hydrocarbon leaks by testing with a combustible gas indicator in the immediate vicinity of the seal, followed, where necessary, by loose shrouding of the seal area, drawing air at a measured rate into the shroud and across the seal by continual evacuation of the atmosphere in the shroud, and the determination of hydrocarbon concentration in the air stream. The equipment setup for testing pump and compressor seals is shown in Figure 3.

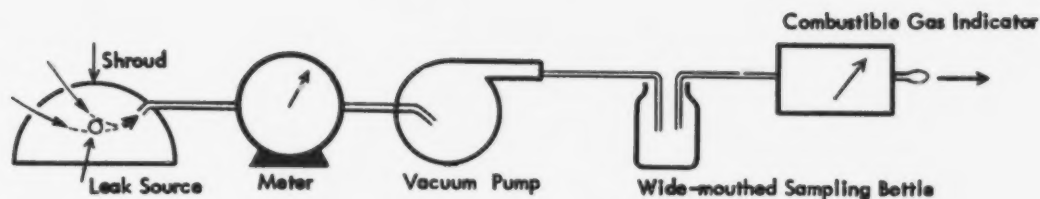


Figure 3. Diagram of equipment for measuring amount of hydrocarbon leakage from pump and compressor seals.

This procedure is basically the method described in the Interim Report of the Joint Project.⁽⁴⁾ Some changes in equipment and procedure were made to increase the range and speed of the tests. With the present setup a crew of three averaged 40 seal inspections daily, including nine complete tests for hydrocarbon emissions. The complete test procedure described below required approximately 20 minutes to complete.

Detecting Hydrocarbon Leaks

The initial test served to locate sources of hydrocarbon emissions and to separate them immediately into large and small leaks. In this test the probe of a combustible gas indicator was held adjacent to the intersection of the moving shaft and the pump casing (Figure 4). While the sample was being drawn the probe was moved completely around this junction. Additional probing checked for leakage around the "take-up" ring and any other joint in the seal structure. The maximum reading of the dial on the combustible gas indicator was recorded. If this reading was greater than 100 per cent of the lower explosive limit (L. E. L.) a complete test was run on the seal. A maximum reading of less than 100 per cent of the L. E. L. indicated a small leak and no further attempts were made to determine the magnitude of emissions from these seals.

(4) Joint District, Federal and State Project for the Evaluation of Refinery Emissions, "Interim Progress Report," July 1956, Los Angeles County Air Pollution Control District.

A constant leakage rate was assigned to all small leaks on pumps and compressors. Any seal having visible liquid leaks received a complete test.



Figure 4. Initial test for hydrocarbon leakage from a pump seal using a Davis Vaportester.

To help assign a reasonable value to small leaks, approximately 15 complete tests were made on seals having small leaks. While there was some overlapping of emission rates from large and small leaks the initial test did differentiate fairly consistently between the two rates. On the basis of these 15 tests emission rates for small leaks were assigned values of one pound per day for pump seals and four pounds per day for compressor seals.

Shrouding the Seal

After locating a large leak, a shroud was placed over the seal area. Since the shape of pumps varies widely no standard technique can be

described. In general, when shrouding centrifugal pumps (Figure 5) heavy duty aluminum foil was placed over the shaft space between the pump and motor.

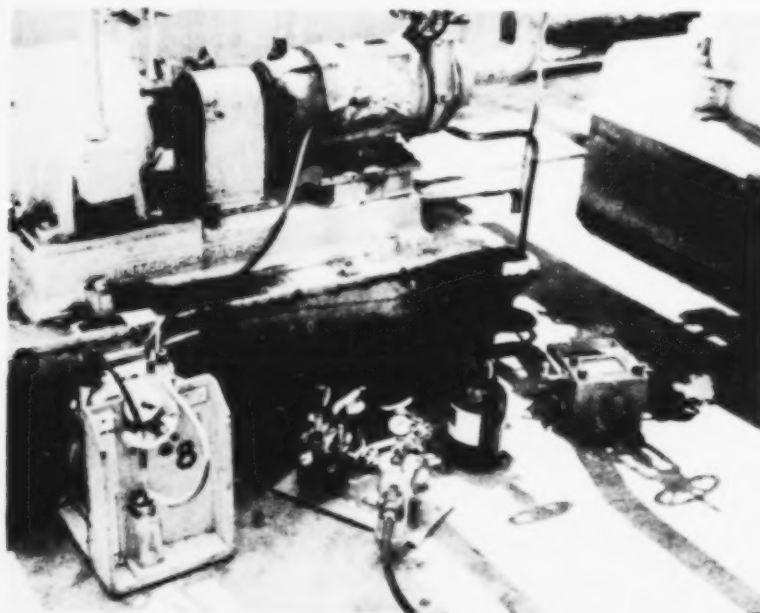


Figure 5. Measuring hydrocarbon leakage from a seal on a centrifugal pump. Air is drawn into the shrouded area at the edges of the aluminum foil and mixes with the hydrocarbons leaking from the seal. The flow rate is measured and the evacuated gas stream is analyzed for hydrocarbon content using a Davis Vapotester.

The foil was crimped at the edges and shaped to fit around the structure. Where possible, masking tape was applied at the junction of the foil and pump casing to hold the foil in place and help effect the closure. When shrouding reciprocating pump seals (Figure 6) aluminum foil was wrapped around the shaft and taped to the pump just behind the seal. This sleeve of foil was then crimped around the moving shaft to complete the shroud.

Compressor seals were generally covered by taping foil over the inspection plate openings as shown in Figure 7.

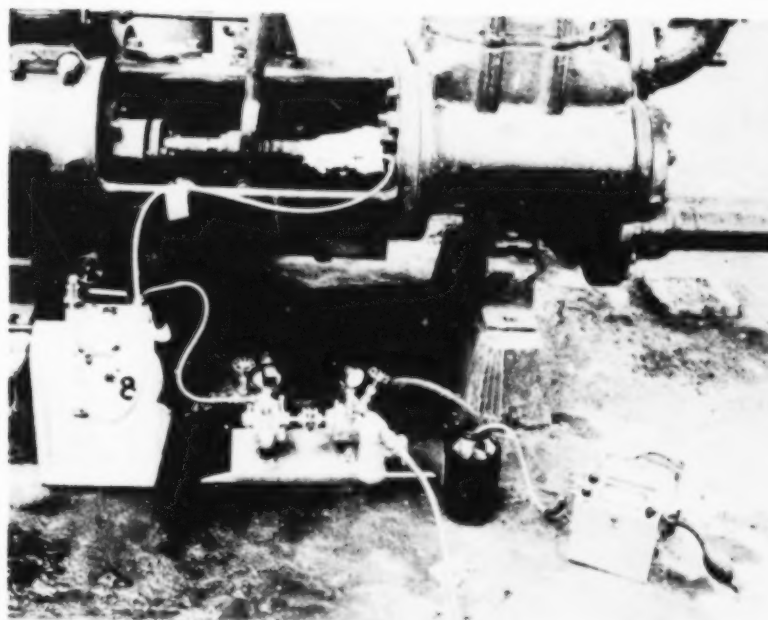


Figure 6. Measuring hydrocarbon leakage from a seal on a reciprocating pump.

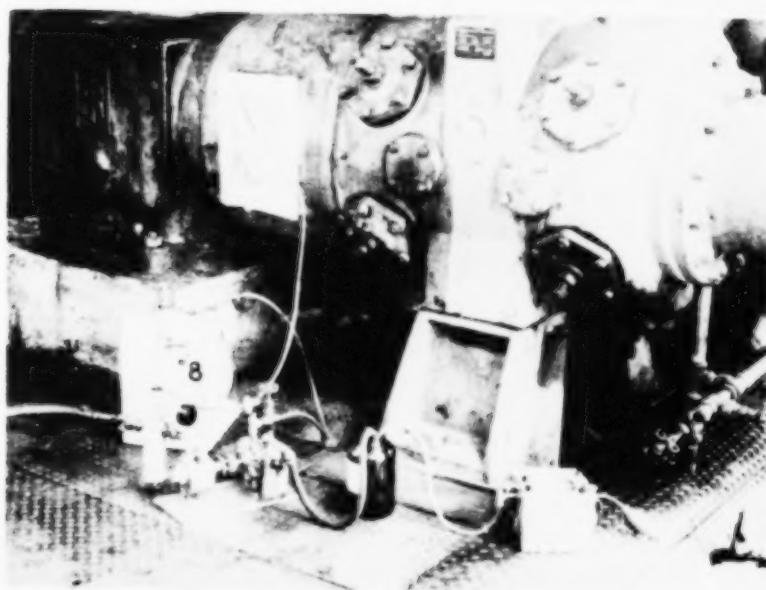


Figure 7. Measuring hydrocarbon leakage from a seal on a gas compressor.

The shroud was made reasonably airtight and holes were punched in the shroud opposite the sampling outlet. This caused the main influx of air to sweep across the seal and helped eliminate short circuiting of the incoming air into the sampling tube.

Sampling

When the shroud was completed, air was drawn in through any openings in the aluminum foil, mixed with hydrocarbons leaking from the seal, and pulled out through the sampling tube. In the original test procedure described in the Joint Project Interim Report⁽⁵⁾ the vacuum pump was placed at the end of the system and the sample for analysis was drawn from an intermediate surge chamber which was under a slight vacuum. Since dilution valves for combustible gas indicators cannot be used when sampling from a chamber at less than atmospheric pressure⁽⁶⁾, grab samples had to be taken for laboratory analysis when large leaks were encountered. The equipment setup actually used in this study and shown in Figure 3 directed the flow from the positive pressure side of the vacuum pump into a wide-mouthed sampling jar. The jar remained at essentially atmospheric pressure and enabled a dilution valve to be used on the combustible gas indicator. Before deciding upon the new procedure a number of tests were run simultaneously on the gas mixture entering and leaving the pump. These showed that no discernible change in hydrocarbon concentrations occurred as the gases passed through the vacuum pump.

The sampling rate was kept at a maximum for most tests. Depending on the pressure of the compressed air available at the test site the vacuum pump used in this study pulled between two and five cubic feet per minute.

In all cases this was sufficient to keep the shrouded area under a slight vacuum and insure air inflow at all openings. The vacuum produced in the shroud was generally about 0.3 inch of water. At the start of each test a check was made for hydrocarbon leakage at the periphery of the shroud using the combustible gas indicator. If this test was positive for hydrocarbons the shroud was sealed tighter, and if possible the sampling rate was increased.

(5) Ibid.

(6) Steigerwald, B., Yates, W., and Dixon, A., "The Determination of Hydrocarbon Concentrations, Using Combustible Gas Indicators," Los Angeles County Air Pollution Control District (October 1957)

The system was then purged until equilibrium conditions were established. A period of two minutes was usually sufficient for pump tests, but compressor tests occasionally required up to ten minutes to reach steady-state loss conditions. When the system was completely flushed of stagnant vapors, the flow rate, meter pressure and gas temperature were recorded. The hydrocarbon content of the gas stream was also determined at this time. Figure 8 shows a complete field data sheet for testing pump seals, and some typical field data.

Analysis

A Davis Vapotester equipped with a series of dilution valves was used to determine hydrocarbon concentrations. Using propane for calculation purposes this equipment allowed determination of concentrations up to 50 per cent by volume in air. On two tests the hydrocarbon concentration exceeded this value and grab samples of the evacuated air stream had to be taken for laboratory analysis. A mass spectrometer or Burrell combustion apparatus was used to analyze for hydrocarbons in these two tests. For smaller leaks, again using propane for calculation purposes, the Vapotester allowed analysis of hydrocarbon concentrations down to 0.02 per cent by volume.

Liquid Leaks

Any seal with a visible emission of liquid hydrocarbon having a Reid vapor pressure greater than 0.5 pound was listed as a large leak and an attempt was made to determine the daily rate of loss to the atmosphere. The testing technique depended upon the volatility of the hydrocarbon and the amount of exposure the liquid received before reaching the drain. In most cases the liquid puddled in a trough just under the seal and flowed through a pipe to the sewer opening. Here the normal test procedure was effective and gave the amount of vapor escaping to the atmosphere. In a number of cases the liquid leaked directly onto the ground or a concrete pad and it was not feasible to shroud the exposed surface of the hydrocarbon. Here, the leakage rate was determined by collection in a graduated cylinder and an estimate (100%, 50%, 0%) was made of vaporization that occurred. Liquid leakage did not make a significant contribution to the total emissions from pump seals.

FIELD TEAM

DATA SHEET - PUMPS

DATE _____

PUMP SURVEY NO. _____

COMPANY _____

Test No.	Pump Designation		Pump Type	Pump Operation	Seals		Product Being Pumped	Initial Test Vapometer Reading	Flow Meter			Final Test Vapometer Reading
	No.	Unit			Type	No.			Press Inch Hg	Temp. °F.	Rate C. F. M.	
1	A16	F.C.C.	CENT.	CONT.	MECH.	1	L.P.G.	0	--	--	--	--
2	A26	F.C.C.	CENT.	CONT.	MECH.	1	GASO.	10	--	--	--	--
3	681.3	LOADING	RECIP.	SPARE	PACK	1	GASO.	100 +	1.6	85	3.8	20 @ DIL. 6:1
								85	--	--	--	--

I - Inboard Seal

O - Outboard Seal

Figure 8. Field testing data sheet for pump testing program including some typical field notes.

Reliability of the Test Procedure

A number of secondary studies were made, both in the laboratory and in the field, in an attempt to arrive at some estimate of the reliability, precision and accuracy of the testing procedures.

Effect of Varying Sample Rates. During three tests on pump seals the air flow rate into the shroud was varied and the hydrocarbon concentration noted at each rate. As shown in Table III, the maximum spread in any of the three series of tests was 0.7 pound per day. The other tests had maximum spreads of 0.2 and 0.4 pound of hydrocarbons per day. The differences observed were generally within the limits of accuracy of the analytical technique, indicating that sampling rate had little effect on the reported emission figure.

Table III

REPRODUCIBILITY OF TEST RESULTS WITH VARYING AIR DILUTION RATES

Sampling Rate C.F.M. @ 60°F. & 760 mm Hg	Hydrocarbon Conc. in Sample Stream, Vol. %	Hydrocarbon Emissions, Lbs/Day
2.5	0.85	5.8
3.0	0.73	5.9
3.4	0.60	5.6
3.6	0.53	5.2
3.9	0.48	5.2

Reliability of the Analytical Technique. The decision to use combustible gas indicators for the determination of hydrocarbon concentrations came after the evaluation of a number of factors. These included the use of these instruments for the initial test, the portable nature of the instruments, the expected types and concentrations of hydrocarbons encountered, and the large number of analyses to be made. Although probably less accurate than more laborious laboratory methods, it was determined that the

accuracy attainable with combustible gas indicators was sufficient for this study. In an effort to substantiate this decision and select the most versatile and reliable combustible gas indicator available to the joint Project, a laboratory study was made on a number of these instruments as part of the pump testing program⁽⁷⁾. Some of the findings of this study are shown in Table IV.

The gasoline test was made on a weathered sample and presented some difficult problems in the selection of a proper lower explosive limit, molecular weight, and in the case of the Davis Vapotester, an instrument calibration curve. These factors greatly affect the calculation of hydrocarbon concentrations. However, when emissions are computed on a weight basis as in the pump and compressor study, errors resulting from poor selection of L. E. L. and molecular weight of the hydrocarbon mixture being tested cancel out (see Calculation Section). Therefore, errors shown for a heterogeneous mixture such as gasoline when comparing concentrations expressed as volume per cent do not apply when discussing errors in losses expressed on a weight basis. Discounting tests on gasoline, the Davis Vapotester gave an average error of 10 per cent for nine tests on a number of pure hydrocarbons.

The use of a dilution valve when high concentrations of hydrocarbons were encountered led to another possible error in the testing procedure. The dilution valve used in this study was supplied by the Davis Emergency Equipment Company with the Model 6 Vapotester. It was calibrated at the beginning of the study. Although a quantitative error was not established for the dilution valve, an evaluation of the deviation from the average dilution factor during the nine calibration runs gives some insight to the reproducibility of this valve. These figures, shown in Table V, are influenced by the possible instrument errors detailed above. Hexane was used for all laboratory tests.

In approximately 50 tests on pumps and compressors, simultaneous grab samples were taken for check analysis by the refinery staff. These samples were analyzed for hydrocarbon content on mass spectrometer or gas chromatographic equipment. Although on individual tests, the hydrocarbon concentrations reported by the refineries varied above and below the values obtained using the Davis Vapotester, the total emissions for the 50 duplicate tests were somewhat lower using the refinery values. Twenty-nine of these checks made at one company had total emissions 28 per cent lower than the Davis Vapotester figure and the remainder of the tests made at four other refineries showed total emissions 4 per cent below the loss figures by the Vapotester method.

(7) Ibid.

Table IV

COMBUSTIBLE GAS INDICATOR TESTS - PER CENT ERROR
FOR VARIOUS HYDROCARBONS

Hydrocarbon	M. S. A. (A)		J. - W (B)		Davis (C)	
	Number of Tests	Avg. Error* %	Number of Tests	Avg. Error* %	Number of Tests	Avg. Error* %
Propane	4	14	2	60	2	4
Hexane	5	16	3	6	3	10
Gasoline	2	37	2	12	2	32
2 Ethyl-1-Butene	2	7	2	20	2	16
Toluene	2	18	2	4	2	8
SUMMARY	15	±17	11	±19	11	±14

* Per cent error equals (Indicated conc. - known conc.) ÷ known conc.

(A) Mine Safety Appliance Explosimeter, Model 2

(B) Johnson - Williams, Model F

(C) Davis Vapometer, Model M-6

Table V

RANGE OF DILUTION FACTORS OBTAINED DURING CALIBRATION
OF THE DILUTION VALVE

Dilution Number	Number of Tests	Average Dilution Factor	Range of Dilution Factors Obtained During Nine Tests	Dilution Factor Used in Study
5	9	5.9	5.2 - 6.7	6
6	9	10.4	8.9 - 11.7	10
7	9	15.9	13.7 - 18.6	16
8	9	24.4	20.2 - 29.8	24

Apparatus and Materials

The following equipment was used in the test procedure described above:

- Combustible gas indicator
- Dilution valve
- Vacuum pump
- Gas meter
- Shrouding materials
- Sampling bottle
- Mine Sampling Tubes
- Stopwatch
- Assorted tubing

Combustible Gas Indicator. Based partially on the results of laboratory tests⁽⁸⁾ the Davis Vapotester, Model 6, was chosen for this study. A spare combustion filament and additional batteries should be carried with the test equipment. A dilution valve should be provided having a number of dilution ratios ranging from 5:1 to 25:1.

Vacuum Pump. A Gast vacuum pump 0740 was used, powered by a Gast air-driven motor, number 4AM. Any explosion-proof unit capable of pulling five CFM at free-flow conditions is adequate for this test procedure. Since the sample must be taken from the pressure or effluent side of the vacuum pump, an aspirator or ejector device cannot be used in place of a pump.

Gas Meter. The flowmeter used was a Sprague dry gas meter Model 1A. Any portable meter capable of measuring air flows up to five cubic feet per minute and withstanding temperatures of 140°F. would be suitable.

Shrouding Materials. Previous pump test procedures^{(9),(10)} used polyethylene sheeting or canvas to shroud the seal area. Aluminum foil, being stiffer and more heat resistant was found to be far superior to either of these for testing both pumps and compressors. In most cases the foil was discarded after one test, although where many similar installations were encountered it was more efficient to reuse the foil a number of times.

(8) Ibid.

(9) Joint Project Interim Report op.cit.

(10) Isham, H. L., "Lubricated Packings for Centrifugal Pumps," Chemical Processing, p. 10 (April 1952).

Approximately 400 feet of 14-inch wide foil were required to shroud 165 seals. Wide masking tape and a can of cleaning solvent complete the list of necessary shrouding materials.

PUMP AND COMPRESSOR SAMPLING PROGRAM

A field sampling program for pump and compressor testing was designed after evaluating the refinery census data and the estimated time required to field test a pump or compressor seal. Field inspections were made on 17 per cent of the existing pump seals and on the entire compressor population.

Pump Testing Program

Based on the reported number of pump seals and the estimated time required to inspect an average seal it was decided to check approximately 15 per cent of the existing pump seals and extrapolate these loss figures to the total pump population. In an attempt to make this extrapolation procedure as accurate as possible pump seals were classified into 27 different groups, the pumps in each group having the same average leak potential. The groups were formed after consideration of the factors which contributed to pump leakage. These include type of seal, product being pumped, type of pump, operation of pump (spare, intermittent, continuous), pressure and maintenance. The first four factors are incorporated directly into the design of the sampling program. Since maintenance is generally a function of refinery policy, its effect was included by applying the above breakdown to each refinery and inspecting 15 per cent of the seals in each group in each refinery. The effect of pressure was not directly included in the program. To avoid any great bias due to oversampling seals in any one pressure range, tests were not limited to any one area of a refinery but some pumps in each group were tested in all major units (alkylation, catalytic cracking, etc.) of the refinery.

For the 27 various groups, Table VI shows the scope and the results of the field testing program on pump seals. A total of 473 seals was inspected. This was 17 per cent of the total 2786 pump seals reported from all refineries. Of the 473 seals inspected, 170 were found to be leaking a total of 2000 pounds of hydrocarbons per day. Ninety-five seals had small leaks and the remaining 75 had large leaks and therefore received a complete test.

Table VI
SCOPE AND RESULTS OF FIELD TESTS ON PUMP SEALS

Group Number*	Total Number of Seals	Seals Inspected		Measured Leaks		Small Leaks		Hydrocarbon Loss From Inspected Pumps, lbs/day
		Number	% of Total	Number	Hydrocarbon Loss, lbs/day	Number	Hydrocarbon Loss, lbs/day**	
1	76	14	18	2	60	2	2	62
2	82	13	16	0	0	2	2	2
3	66	12	18	0	0	2	2	2
4	127	21	17	6	294	7	7	2
5	266	59	22	3	19	13	13	301
6	56	16	28	0	0	5	5	32
7	163	34	21	13	262	6	6	5
8	191	35	18	2	23	4	4	268
9	150	19	13	2	7	2	2	27
Subtotal	1177	223	19	28	665	43	43	9
10	92	15	16	5	26	2	2	708
11	78	9	12	1	4	2	2	28
12	68	9	13	0	0	3	3	6
13	49	0	0	0	0	0	0	3
14	179	21	12	12	83	5	5	0
15	103	18	18	0	0	3	3	88
16	100	15	15	6	280	4	4	3
17	175	26	15	6	226	11	11	284
18	124	25	20	2	16	0	0	237
Subtotal	968	138	14	32	635	30	30	16
19	26	6	23	1	23	3	3	665
20	32	5	16	0	0	0	0	26
21	38	8	21	0	0	3	3	0
22	72	13	18	6	383	3	3	3
23	173	29	17	1	71	7	7	386
24	150	17	11	0	0	0	0	78
25	60	7	12	4	19	2	2	0
26	40	7	18	3	82	3	3	21
27	50	20	40	0	0	1	1	85
Subtotal	641	112	17	15	578	22	22	1
TOTALS	2786	473	17	75	1878	95	95	600
								1973

* Group numbers represent a specific combination of pump type, seal type, pump operation and product. These are detailed in Table I.

** A value of one pound per day was assigned to a small leak on a pump seal.

Compressor Testing Program

The physical arrangement of compressors in oil refineries and the numbers involved in the compressor program made it feasible to inspect all the units in local refineries. Since a number of installations were "down" for repairs at the time of the tests, only 326 of the existing 345 seals were actually tested. As shown below the 90 measured leaks and 87 small leaks lost a total of 2800 pounds of hydrocarbons per day.

Total number of compressor seals	345	
Seals inspected	326	
Measured leaks	90	
Hydrocarbon loss, pounds per day		2423
Small leaks	87	
Hydrocarbon loss, pounds per day*		348
Total hydrocarbon loss from inspected seals, pounds per day		2771

* A value of four pounds per day was assigned to any small leaks on compressor seals.

DATA EVALUATION

Total Emission of Hydrocarbons from Pumps and Compressors

Since essentially all compressors which were reported were tested, no elaborate sampling nor data extrapolation procedure was necessary for this group of seals. Nineteen compressor seals were "down" for repair at the time of the tests. It was assumed that these 19 seals had the same average emission as the 326 seals which were tested. The tabulation above details the source of the 2800 pounds of hydrocarbons per day observed being lost by leakage during the field tests. The contribution of the additional 19 untested seals gives a total loss from compressor seals of 1.5 tons of hydrocarbons per day.

The field tests on pump seals showed about 2000 pounds per day of hydrocarbons being emitted from approximately 17 per cent of the reported pump seals. A number of techniques can be used to expand the field data to the entire pump population. These all involve segregation of the data into logical groups, calculation of an average for the seals inspected in

that group, expansion of this average to the total number of seals in that group, and summation of the contribution of each group for a total loss figure. Since the sampling program was weighted for the parameters causing leaks in pump seals, the field data yielded a total loss figure of 6 tons per day regardless of the extrapolation technique. The most specific and informative data expansion, detailing the contribution of each of the 27 sampling groups, is shown in Table VII.

Reliability of Loss Figures

Test Procedure. As described earlier (TEST PROCEDURE) the analytical error from both the Davis Vapotester and the dilution valve was probably less than ± 20 per cent.

Data Extrapolation. A statistical analysis was made of the data on pump seals in an attempt to arrive at confidence limits for the total emission figure. As expected from a consideration of maintenance procedures, the individual seal losses were highly skewed toward the small leaks, and the usual statistical techniques which assume a normal frequency distribution of values around the arithmetical mean could not be used. However, by assuming that the seals with zero leaks actually had very small leaks (under 0.25 pound per day), the logarithms of the individual loss values did approximate a normal distribution curve, and confidence limits could be developed for the geometric mean of the data. The geometric mean was 0.15 pound per day and had 95 per cent confidence limits of 0.12 and 0.19 pound per day. This means that 19 out of 20 times the geometric mean of 473 pump tests will fall between 0.12 and 0.19 pound per day. While these limits cannot be explicitly transposed to the arithmetic mean, they do give an idea of the reliability of the pump data.

A more rigorous analysis was made for the accuracy of the data in predicting the number of leaks that would occur in the total pump population. Using techniques described by Fisher and Yates⁽¹¹⁾ it can be stated with 95 per cent confidence that the frequency of leaks occurring in the total population will be within ± 3 per cent of the value predicted by the test data. This applies only to the number of leaks and not to the amount of leakage.

(11) Fisher, R. A., Yates, F., "Statistical Tables for Biological, Agricultural and Medical Research," Table VIII, Oliver and Boyd Ltd., London (1943)

Table VII

EXTRAPOLATION OF FIELD DATA BY SAMPLING GROUPS
TO OBTAIN A TOTAL LOSS FIGURE

1	2	3	4	5	6
Group Number(*)	Total Number of Seals	Number of Seals Inspected	Hydrocarbon Loss From Inspected Seals, Lbs. /Day	Average Hydrocarbon Loss Per Inspected Seals, Lbs. /Day (4) (3)	Total Hydrocarbon Loss Lbs. /Day (5)x(2)
1	76	14	62	4.4	335
2	82	13	2	0.2	16
3	66	12	2	0.2	13
4	127	21	301	14.4	1830
5	266	59	32	0.6	160
6	56	16	5	0.3	17
7	163	34	268	7.9	1289
8	191	35	27	0.8	153
9	150	19	9	0.5	75
10	92	15	28	1.8	166
11	78	9	6	0.7	55
12	68	9	3	0.3	20
13	49	0	---	---	---
14	179	21	88	4.2	752
15	103	18	3	0.2	21
16	100	15	284	18.8	1880
17	175	26	237	9.1	1592
18	124	25	16	0.6	74
19	26	6	26	4.3	112
20	32	5	0	0	0
21	38	8	3	0.4	15
22	72	13	386	29.6	2131
23	173	29	78	2.7	467
24	150	17	0	0	0
25	60	7	21	3.0	180
26	40	7	85	12.1	484
27	50	20	1	0.1	5
TOTALS	2786	473	1973	4.2	11,842 or 6 tons per day

(*) Group numbers represent a specific combination of pump type, seal type, pump operation, and product. These are detailed in Table I.

Calculations

The first calculation necessary is common to both the pump and compressor tests. The flow rate observed in the field must be converted to standard cubic feet per minute.

The following formula was used:

$$\text{S.C.F.M.} = \text{C.F.M.} \times \frac{520}{T_o + 460} \times \frac{29.92 - P_o}{29.92}$$

Where

S.C.F.M. = Standard cubic feet per minute, 60°F. and 29.92 inches of mercury.

C.F.M. = Observed cubic feet per minute at test conditions.

T_o = Observed temperature at flowmeter, °F.

P_o = Observed vacuum at flowmeter, inches of mercury.

For tests on pump seals the following formula was used to calculate the loss:

$$\text{H.C.} = \frac{\text{C.D.R.} \times 1440 \times \text{S.C.F.M.} \times \text{L.E.L.} \times \text{M.W.}}{379}$$

Where

H.C. = Hydrocarbon emission in pounds per day

C.D.R. = Corrected Davis Vapotester reading (fraction of lower explosion limit). To arrive at the true fraction of the L.E.L. a correction must be made on the Vapotester reading observed in the field. This is done using a series of calibration curves supplied with the Davis instrument. This correction varies with the type of hydrocarbon and to a lesser degree with the observed concentration of the hydrocarbon. When testing hexane, the correction lowers the field observation by about 5 per cent. With propane the correction is about minus 30 per cent. Except where accurate definition of the product was possible, an assumed calibration curve lying between the propane and pentane curves was used when testing for the highly volatile hydrocarbons. For pumps handling gasoline and naphtha-range hydrocarbons, the curves for pentane and hexane were used respectively.

For the hydrocarbons encountered in this study the product of the L.E.L. (lower explosive limit) and M.W. (molecular weight) is approximately 1.03 and can be incorporated in the numerical constant. This reduces the importance of being able to identify the hydrocarbons in the combustible mixture and is a distinct advantage of this analytical technique. The above formula then reduces to

$$H.C. = 3.9 \times C.D.R. \times S.C.F.M.$$

Compressor gases often contain large quantities of hydrogen. When this element was present the hydrocarbon emissions were calculated using the formula:

$$H.C. = 3.9 \times C.D.R. \times S.C.F.M. \times \frac{(100-A)}{(100)}$$

Where

C.D.R. = Corrected Davis Vapometer reading (fraction of L.E.L.). Unless an accurate definition of the compressor gases was available, the curve for propane was used to find the correction to the observed Davis reading.

A = Per cent of hydrogen in the gas being compressed. Compressors with "A" values greater than 85 per cent were not included in this study.

Discussion

The data collected during this study, aside from yielding a total air pollution estimate for pump and compressor seals, were used to evaluate the efficiency of the various seals, identify the worst offenders, and define the contribution of the various hydrocarbons to the total air pollution estimate.

Comparison of Mechanical and Packed Seals. Table VIII gives a comparison of the effectiveness of mechanical and packed seals on the three classes of hydrocarbons used in this study. The slight difference between the average loss from mechanical and packed seals when handling highly volatile hydrocarbons needs further clarification. When in continuous service the average loss per seal was 18.8 and 7.9 pounds per day for packed and mechanical seals, respectively, indicating that mechanical seals are far more efficient when running continuously. On spare or standby service the packed seals are more effective, losing 1.8 pounds per day to an average loss of 4.4 pounds from mechanical seals. Since no tests were made on packed seals on centrifugal pumps handling light products on an intermittent basis, a comparison

cannot be made on seals in this service. However, mechanical seals in this group lost an average of 14.4 pounds per day, almost twice the loss for mechanical seals in continuous service on light products.

Reciprocating pumps handling light products are the worst offenders both in leak incidence and magnitude of average emission. The largest leak encountered in this study, 266 pounds per day, was from a reciprocating pump on intermittent service pumping L.P.G. (Reid vapor pressure greater than 26 pounds). The pump was idle at the time of the inspection.

Average Losses by Product Being Pumped. Table IX shows average losses by type of product being pumped. As expected, the highly volatile hydrocarbons were the most difficult to seal with 28 per cent of the total number of seals accounting for 70 per cent of the total emissions.

Average Seal Losses by Refinery and Refinery Throughput. In an attempt to arrive at some factors for estimating seal losses the pump and compressor data were compared by refinery and unit of refinery throughput. The results are shown in Table X. It appears from the threefold spread in both pump and compressor average emissions that large errors in estimating losses from any one refinery could result by applying the overall average to an individual refinery. A wide variance can also be noted in losses per 1000 barrels of refinery throughput.

Table VIII

EFFECTIVENESS OF MECHANICAL AND PACKED SEALS
ON VARIOUS TYPES OF HYDROCARBONS

Seal Type	Pump Type	Type Hydro-carbon Being Pumped, Pounds Reid	Average Hydro-carbon Loss Per Inspected Seal, Pounds/Day	Leak Incidence	
				Small Leaks,* % of Total Inspected	Large Leaks, % of Total Inspected
Mechanical	Centrifugal	>26	9.2	19	21
"	"	5-26	0.6	18	5
"	"	0.5-5	0.3	19	4
Average	"	>0.5	3.2	19	13
Packed	Centrifugal	>26	10.3	20	37
"	"	5-26	5.9	32	34
"	"	0.5-5	0.4	12	4
Average	"	>0.5	4.8	22	23
Packed	Reciprocating	26	16.6	31	42
"	"	5-26	4.0	24	10
"	"	0.5-5	0.1	9	0
Average	"	>0.5	5.4	20	13

* Small leaks lose less than one pound of hydrocarbon per day.

Table IX
AVERAGE PUMP SEAL LOSSES
BY VOLATILITY OF PRODUCT BEING PUMPED

Product, Pounds Reid	Total Number of Seals Reported	Number of Seals Inspected	Average Hydrocarbon Loss per Inspected Seal, Pounds per Day
26	765	125	11.1
5-26	1216	204	2.7
0.5-5	805	144	0.3

Table X
AVERAGE SEAL LOSSES FOR INDIVIDUAL REFINERIES

Refinery*	Average Hydrocarbon Loss per Inspected Seal, Pounds per Day		Hydrocarbon Loss, Pounds per Day per 1000 Barrels of Refinery Throughput	
	Pumps	Compressors	Pumps	Compressors
A	5.3	12.4	25.4	6.7
B	4.4	8.4	20.8	3.1
C	4.6	6.1	35.0	3.8
D	4.7	9.3	11.8	3.0
E	2.3	9.4	5.6	2.8
F	1.7	4.5	4.8	2.7
Summation	4.0	8.5	15.7	3.7

*Only the major refineries are listed.

CONCLUSIONS

1. The study detailed in this report allowed a reasonable estimate of hydrocarbon emissions to the atmosphere from seals on pumps and compressors in oil refineries in Los Angeles County. Hydrocarbon losses through pump seals total about 6 tons per day and emissions from compressor seals are about 1.5 tons per day.
2. When installed on pumps in continuous operation mechanical seals are more effective than packed seals in reducing losses from pumps. When installed on pumps in spare and particularly intermittent service mechanical seals lose much of their effectiveness and may be less efficient than packed seals for intermittent operation.
3. Pumps handling highly volatile materials (products having a Reid vapor pressure greater than 26 pounds) contribute most of the total hydrocarbon leakage through pump seals. The pumps in this group comprise 28 per cent of the total number and are responsible for 70 per cent of the total emissions.
4. The testing procedures developed for this study and detailed in this report provide a feasible way to test pump and compressor seals for hydrocarbon leakage.